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## **INVITED SPEAKER**

### **Health Monitoring Technology for Thermal Protection Systems on Reusable Hypersonic Vehicles**

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Integrated subsystem health diagnostics is an area where major improvements have been identified for potential implementation into the design of new reusable launch vehicles (RLVs) in order to reduce life cycle costs, to increase safety margins, and to improve mission reliability. This talk summarizes a joint effort between NASA Ames and industry partners to develop rapid non-contact diagnostic tools for health and performance monitoring of thermal protection systems (TPS) on future RLVs. The specific goals for TPS health monitoring are to increase the speed and reliability of TPS inspections for improved operability at lower cost. The technology being developed includes a 3-D laser scanner for examining the exterior surface of the TPS, and a subsurface microsensor suite for monitoring the health and performance of the TPS. The sensor suite consists of passive overlimit sensors and sensors for continuous parameter monitoring in flight. The sensors are integrated with radio-frequency identification (RFID) microchips to enable wireless communication of the sensor data to an external reader that may be a hand-held scanner or a large portal. Prototypes of the laser system and both types of subsurface sensors have been developed. The laser scanner was tested on Shuttle Orbiter Columbia and was able to dimension surface chips and holes on a variety of TPS materials. The temperature-overlimit microsensor has a diameter under 0.05 inch (suitable for placement in gaps between ceramic TPS tiles) and can withstand 700°F for 15 minutes.

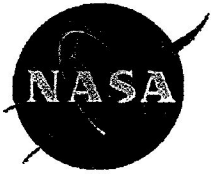


# Health Monitoring Technology for Thermal Protection Systems on Reusable Hypersonic Vehicles

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# Outline

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- Introduction
- TPS inspection and health monitoring
- Surface scanning technology
  - Prototype surface scanner
- "Wireless" technology for TPS sensors
  - Prototype passive sensor
  - Prototype active sensor
- Future work



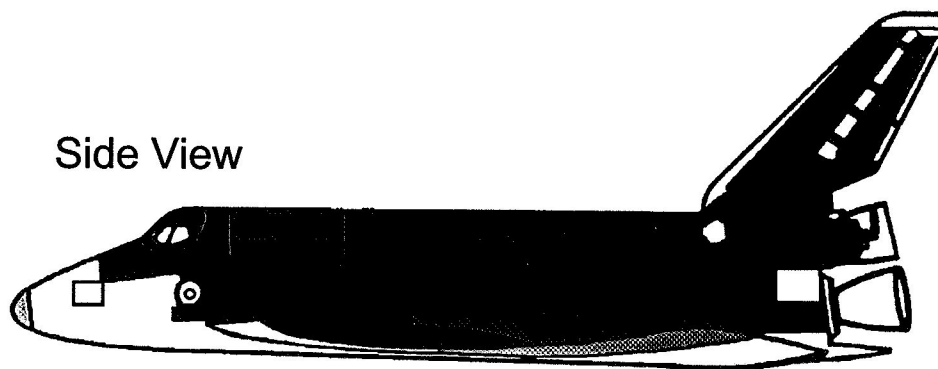


# Shuttle Thermal Protection System

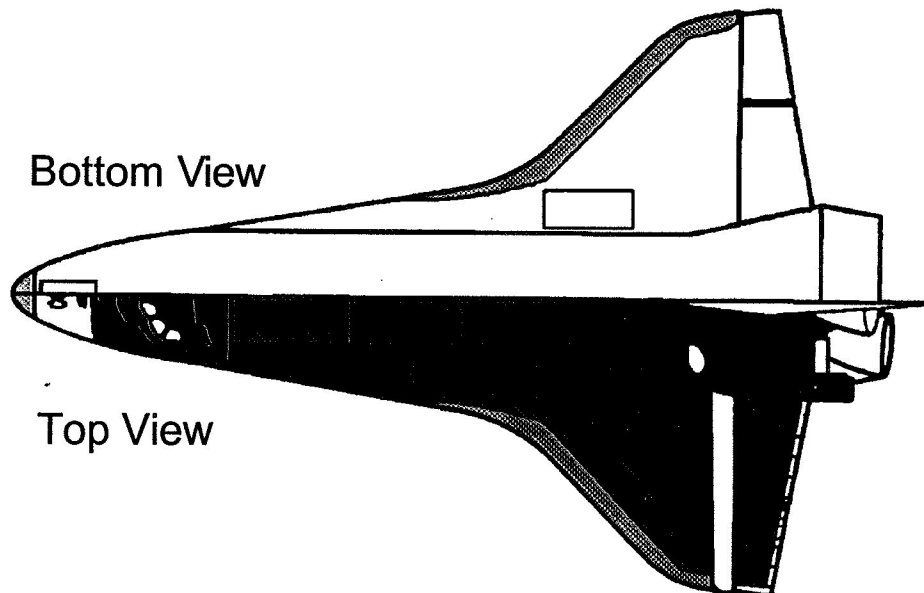


Reinforced Carbon-Carbon	
RCG (Black Glass) Coated Tiles	
White Glass Coated Tiles	
AFRSI Blanket Insulation	
FRSI Blanket Insulation	
Metal or Glass	

Side View



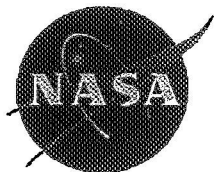
Bottom View



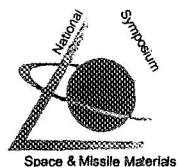
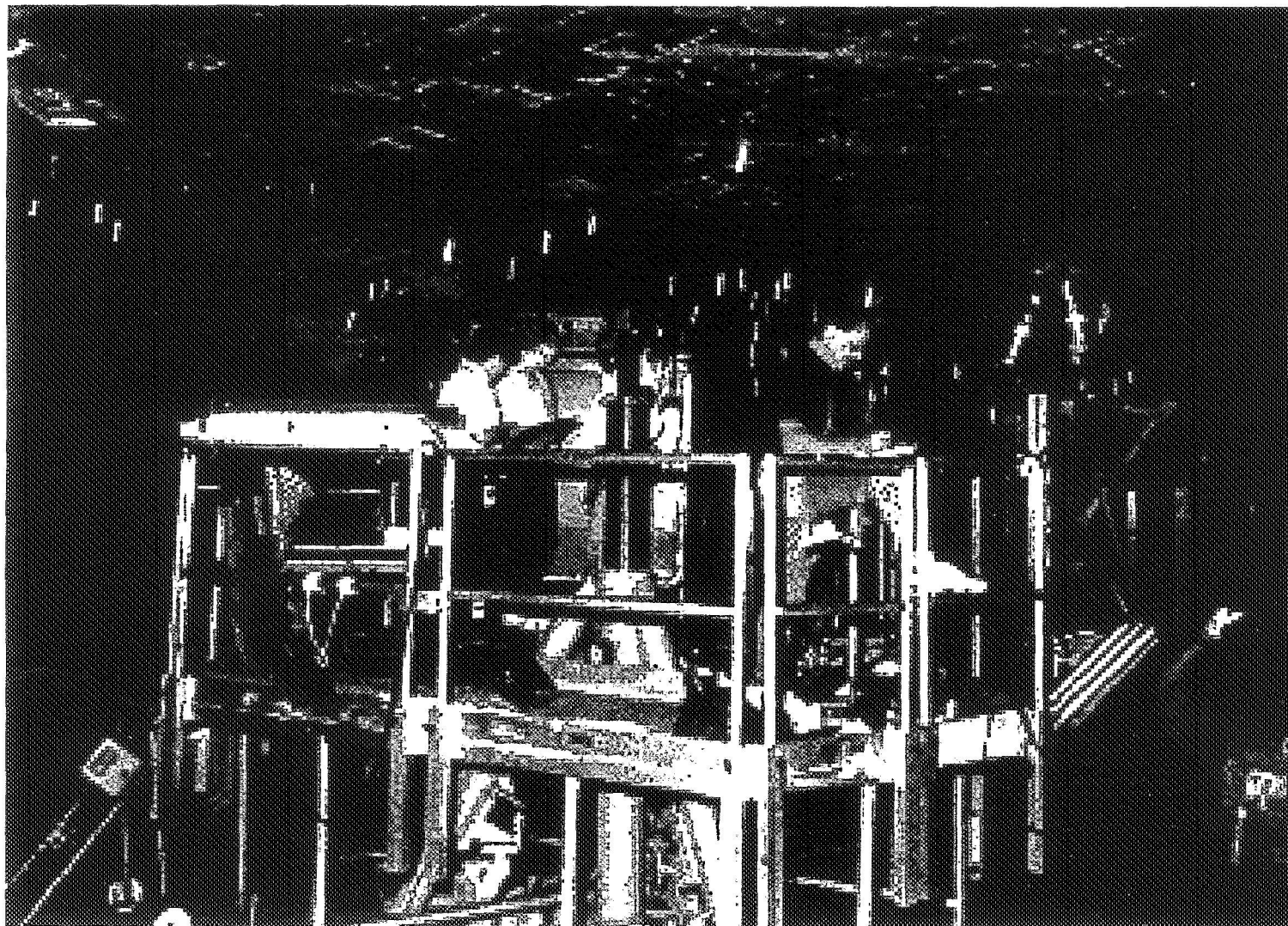
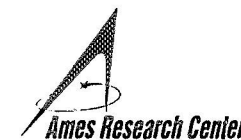
Top View







# Shuttle TPS Inspection & Maintenance



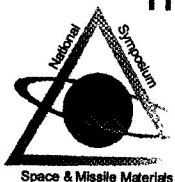


# Historical Perspective & Motivation

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- NASA is funding development of technologies to lower cost and to increase reliability and safety for reusable launch vehicles (RLVs).
  - One goal is to reduce costs by factor of 10.
- TPS ground operations account for about 25% of the life-cycle cost for the Shuttle fleet (assuming a 100-mission life).
  - Current procedures rely on humans to perform a detailed close-range visual inspection of the TPS to identify defects and to dimension them as required for disposition (ignore, repair, replace).
  - Inspection of gaps between 20,000+ TPS tiles is the most time-consuming and tedious activity.
- Compared with Shuttle procedures, ground operations for future RLVs need lower personnel costs and much faster turnaround time.
- NDE technology is expected to make future TPS inspection activities more automated, more reliable, and quicker than human inspection.





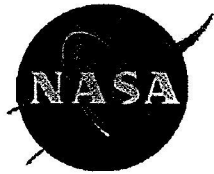
# Goals

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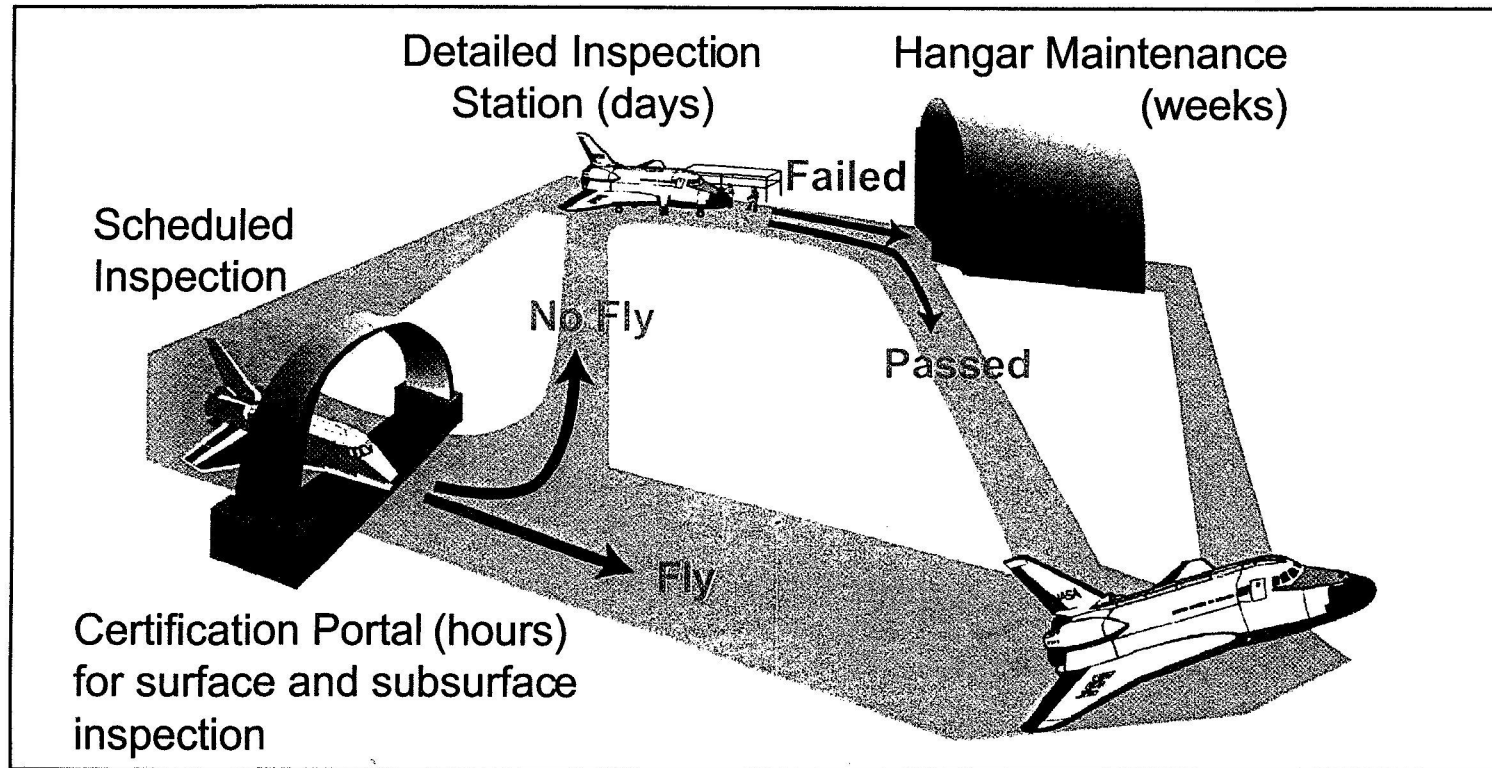


- We want to develop rapid and reliable TPS inspection (health verification) technology for Shuttle and future RLVs.
- Most surface defects can be detected and measured using laser scanning technology from outside the vehicle.
  - Develop smart hand-held or automated tools to expedite tasks that are tedious or time consuming
  - Reduce inspector variability and human judgement
- Subsurface defects can be detected using subsurface sensors
  - Develop/use a suite of sensors to provide subsurface health verification and defect detection
  - Use wireless communications technology to pass information from the sensors to outside the TPS (or to inside the vehicle)
  - Avoid unnecessary TPS removals





# Futuristic TPS Inspection Process



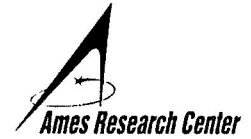
- The portal inspects the TPS as the vehicle passes.
  - Scan the exterior surface for damage.
  - Query the status of subsurface health sensors.
- Alternatively: automated scanning heads or small robots can perform the inspection.





# Inspection Requirements Definition

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A list of system requirements was developed cooperatively by IVHM, TPS, and sensors experts and Shuttle operations personnel at Kennedy Space Center.

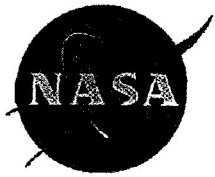
## For remote NDE inspection

- rapid for fast vehicle turnaround
- high reliability and reproducibility
- reasonable development and implementation cost
- safe for humans and vehicles
- no excessive database or data processing requirements
- applicable to all types of TPS
- integrates with the vehicle IVHM system

## For TPS subsurface sensors

- low mass and volume
- no adverse impact on TPS thermal or mechanical performance
- minimal impact on TPS costs
- indefinite lifetime or easy repair, maintenance
- no wiring between TPS parts
- must survive adverse environmental conditions





# Surface Scanning

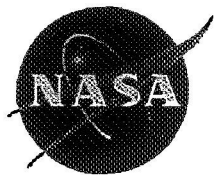
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- Shuttle TPS inspections use human vision
  - Defects are identified
  - Holes, steps, and gaps are dimensioned using measurement tools
- A laser step-and-gap tool can be used in some locations
  - Device measures gap width, gap depth, and step height
  - Too large and outdated
- Boeing and KSC want modern, portable (hand-held) tools to dimension steps, gaps, and holes.
  - NASA Ames was funded to develop a prototype laser scanner
  - TPS-IVHM supported this work







# Laser Surface Measurement Tool

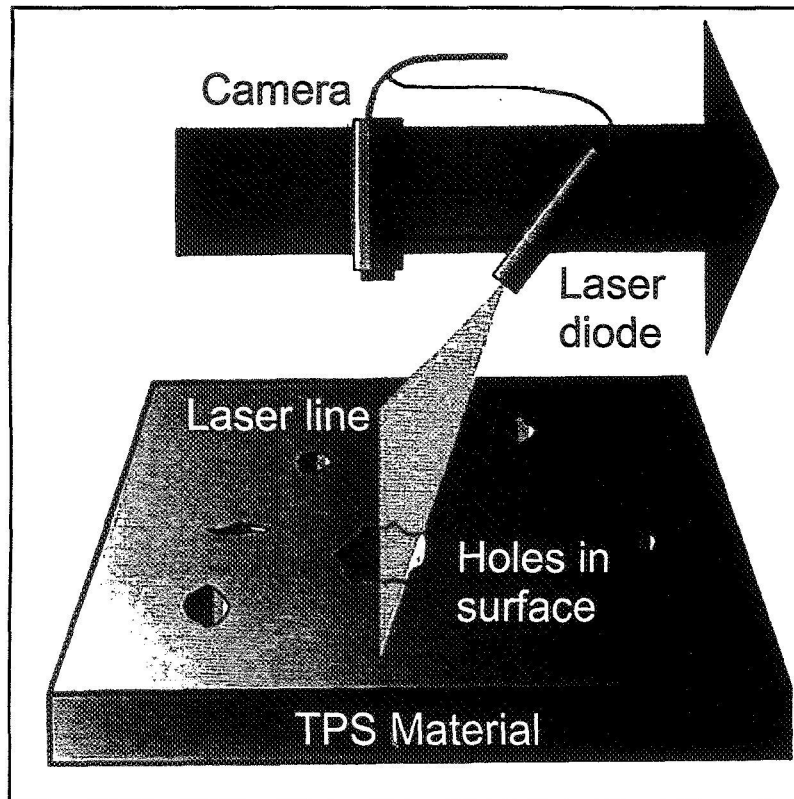
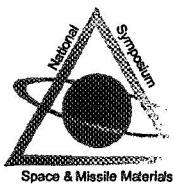


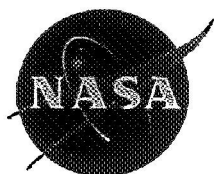
Image of coins and holes from prototype (shading indicates depth)



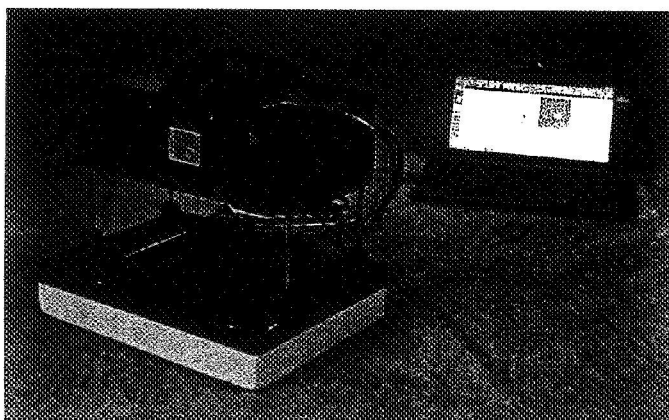
## Theory of Operation

- The camera/laser sensor head moves across the surface.
- A straight laser line is projected down onto the surface at an angle from normal.
- Distortions in the reflected line indicate the depth of the surface.
- The prototype uses two lasers to eliminate masking effects.

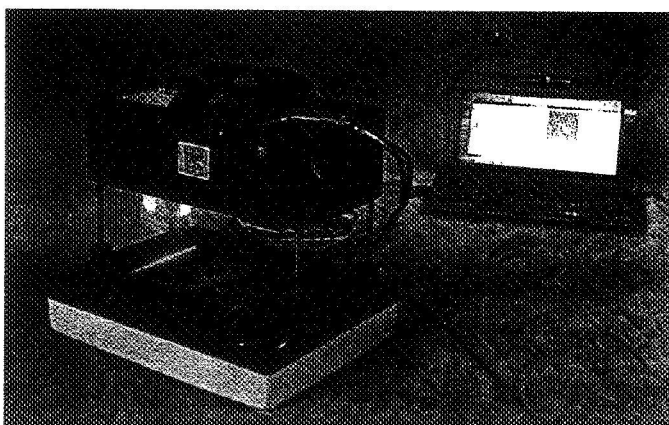




# Prototype Scanner



Scanner positioned on tile



Scanning

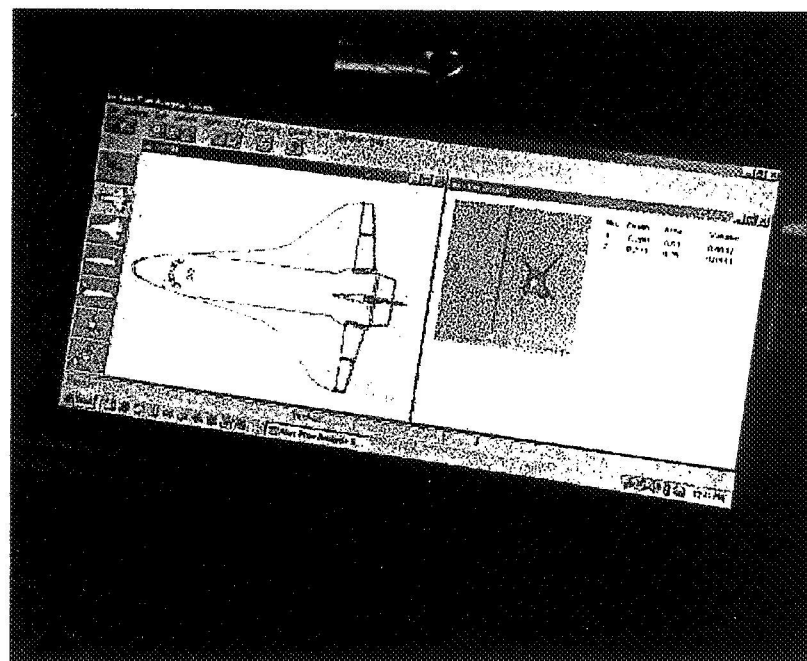


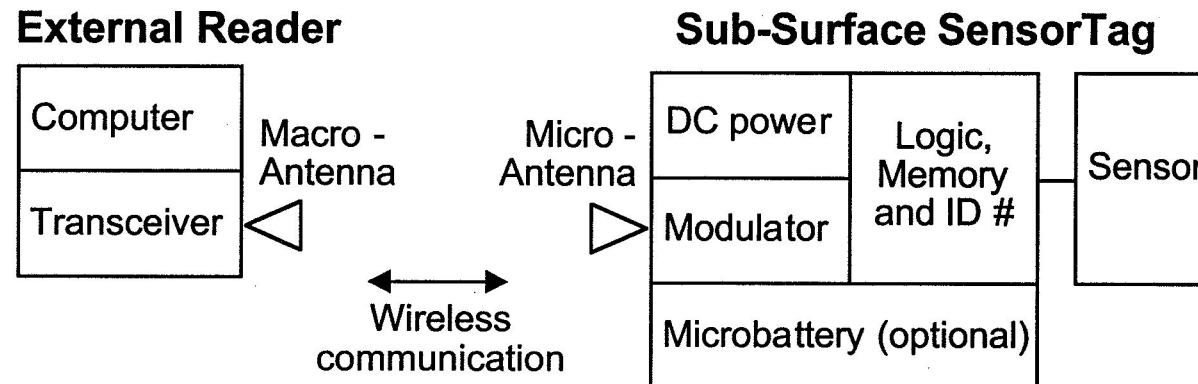
Image viewed in Boeing software







# "SensorTag" System Block Diagram

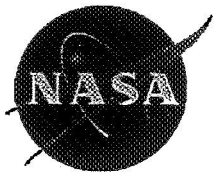


Combine radio-frequency identification (RFID) tags with event-recording sensors to provide subsurface inspection with wireless communication.

## Features:

- Each tag is independent and has a unique identification number.
- Anti-collision technology allows fast non-contact inspection of many SensorTags.
- Reader energizes (or rouses) circuit which transponds its ID number and sensor data.
- Optional microbattery provides power for in-flight data acquisition.
- Reader interfaces with computerized records of TPS/sensor history.

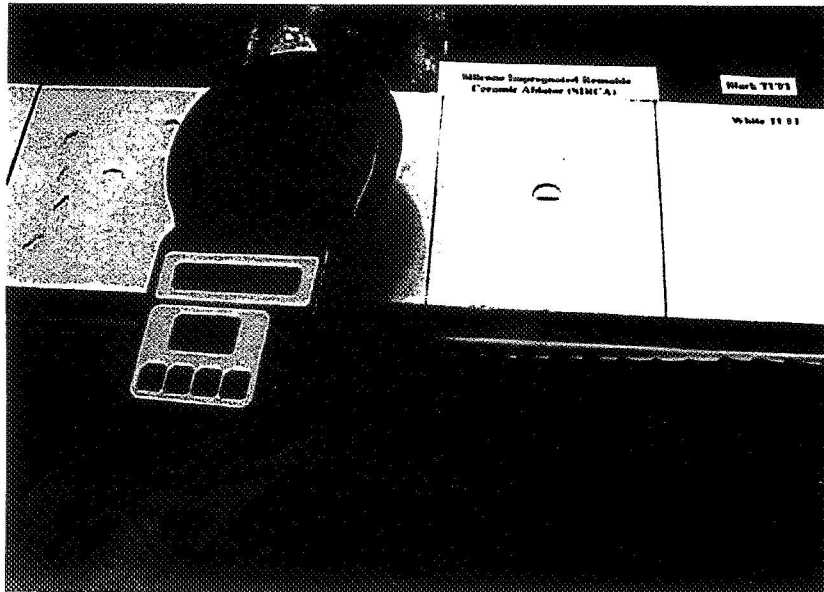




# Wireless Technology Demonstrations



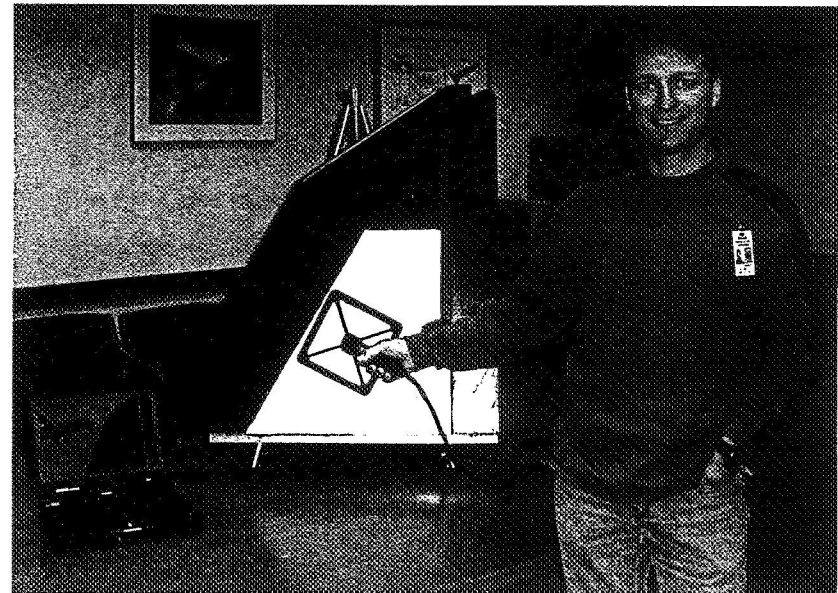
## Communication through TPS



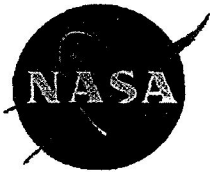
- testbed contains various TPS materials
- use small off-the-shelf reader and rice-grain shaped RFID tag (insert, 73 mg)
- read range of about 10 cm at 125 kHz
- variations of  $\pm 10\%$  depending on materials



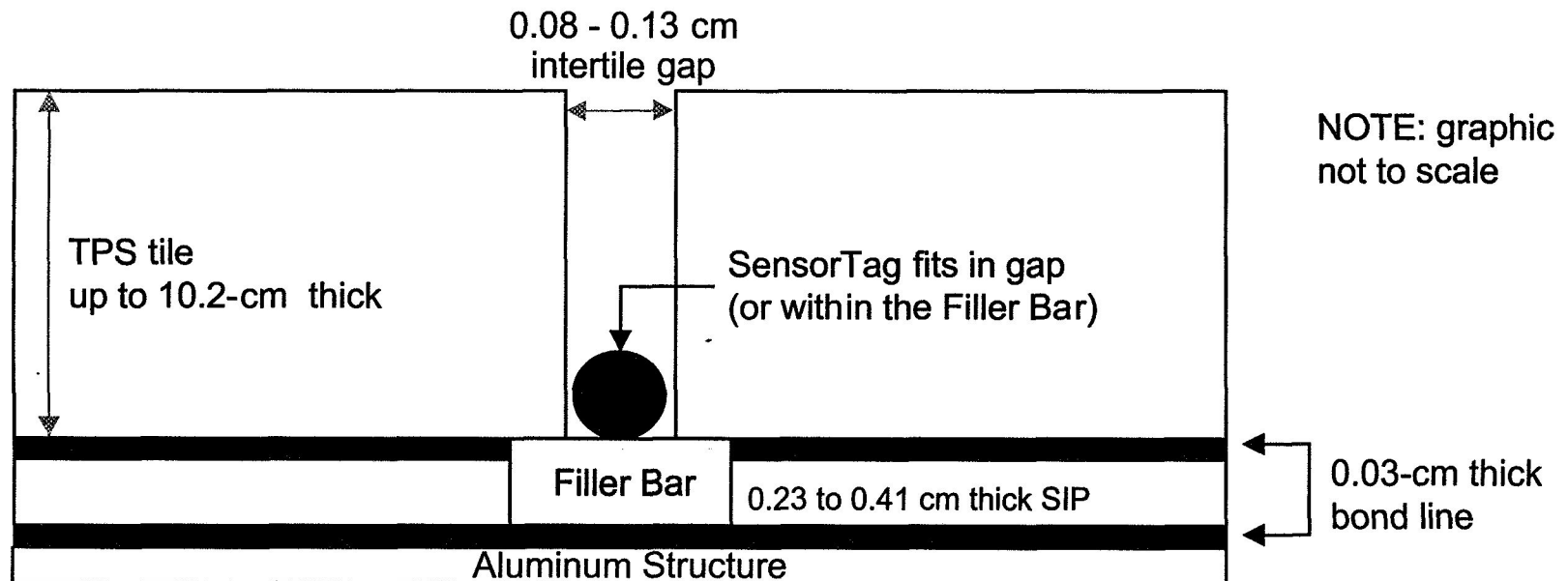
## "Anticollision" Technology



- wing-shaped article has TPS covering over 100 RFID tags
- easily read all tags in under 1 minute
- read range of about 30 cm using 18-cm reader operating at 125 kHz
- to read 50,000 tags in 1 hour, may need multiple receivers and/or faster circuits (e.g. using 13.56 MHz or 900 MHz RFIDs)



# Geometry for Tile-Gap SensorTag



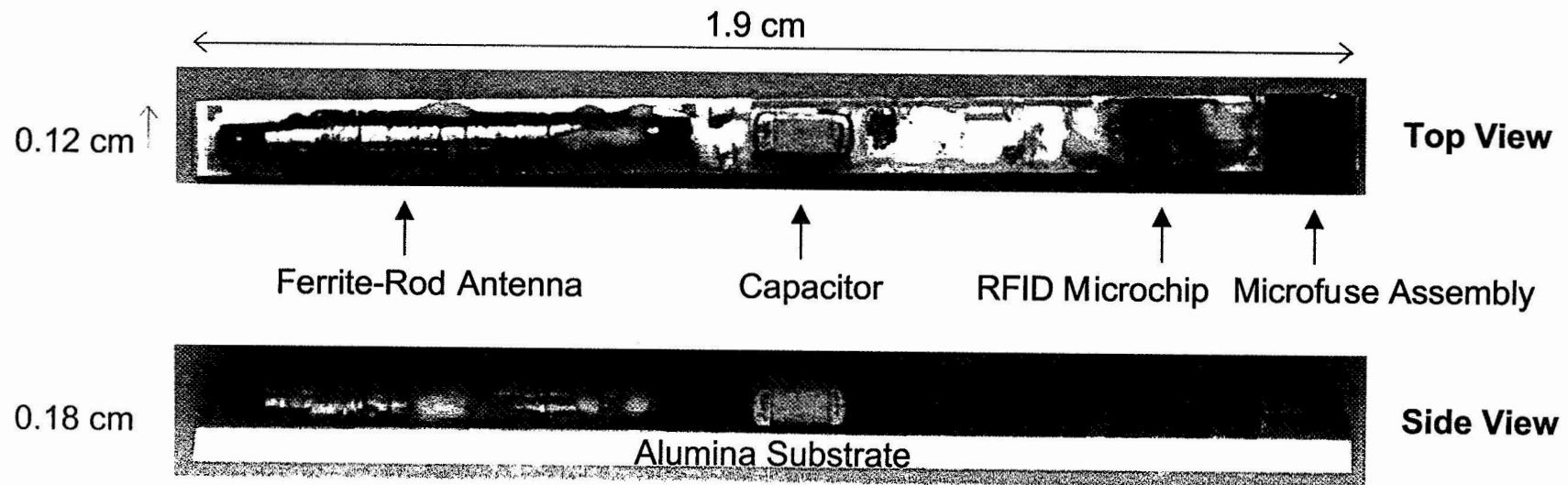
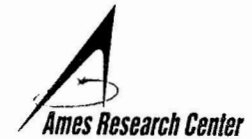
## SensorTag:

- is located at bottom of inter-tile gap.
- must detect and indicate occurrence of temperatures high enough to char sub-surface components (about 290°C).
- must survive short-term exposure to 345°C or higher.
- does not need to be reusable above the over-limit temperature.
- may be passive (no battery required).





# Prototype Tile-Gap SensorTag



- Lateral dimension of 0.12 cm allows insertion into larger gaps.
- Mass of 80 mg (10,000 SensorTags is less than 1 kg).
- All components can survive long-term exposure to 315°C, except
  - the microfuse irreversibly opens at a prescribed temperature.
  - EEPROM-based RFID could suffer memory loss.
- Oven tests show the device still functions after 15 minutes at 400°C. The polyimide wire insulation and epoxy adhesive turn black.

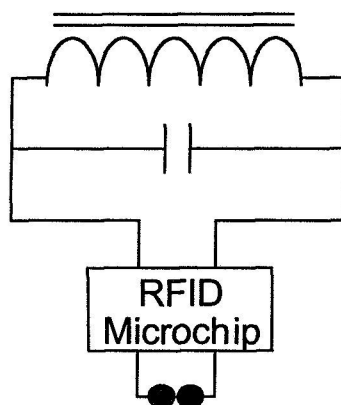




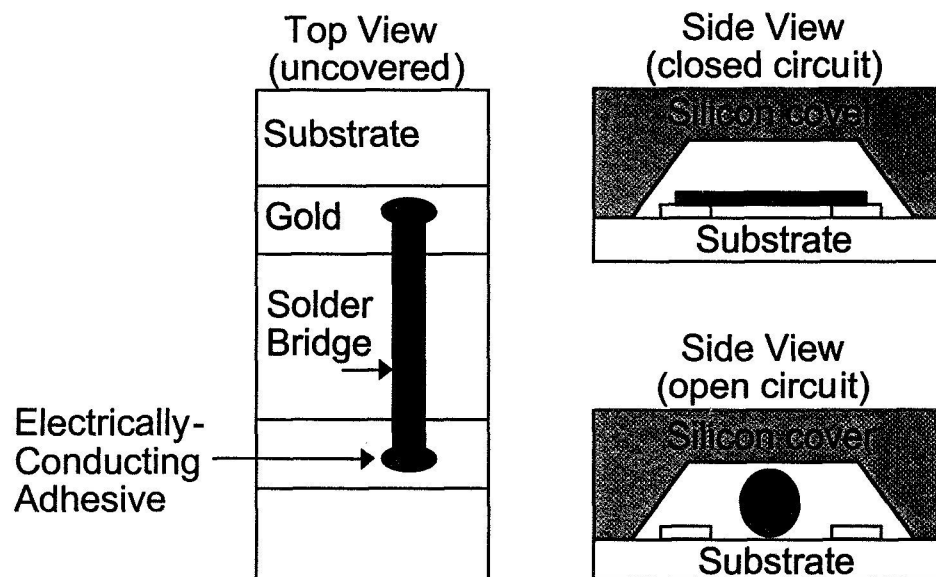
# Circuit Diagram and Custom Microfuse



Circuit Diagram



Microfuse Design



- Circuit takes advantage of switch port on MCRF202 chip.
  - Circuit resonant frequency is 125 kHz.
  - Switch closed (solder intact): transpond normal ID code (a 64 to 256 bit number).
  - Switch open (solder melted); transpond a bit-inverted ID code.
- Oven tests confirm operation of microfuse.
  - Eutectic solder melts quickly at 292°C to open the circuit.



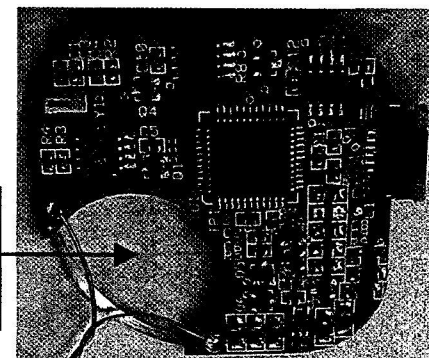


# Prototype Active Thermal SensorTag



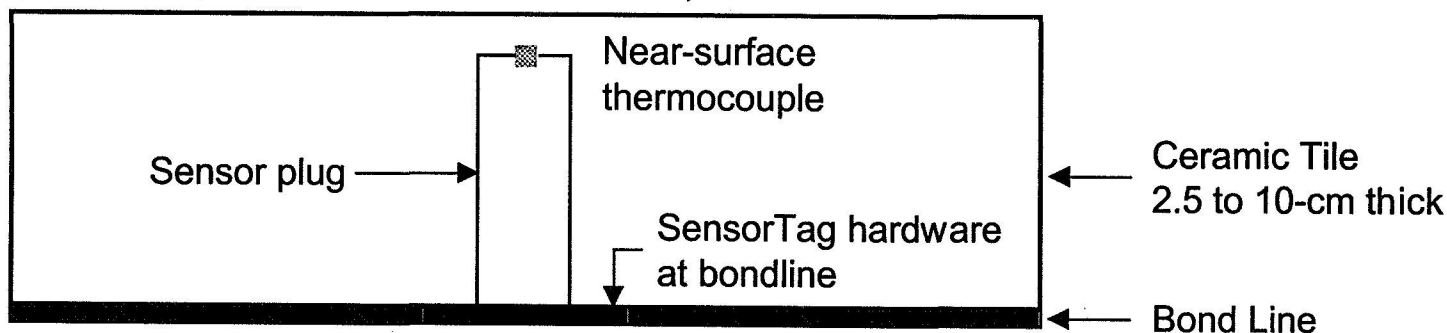
- Tile sensor plug bonded to SensorTag, this assembly then inserted into tight-fitting hole at back of tile.
- Periodically monitors temperatures at bond line and near the surface.
- Time-tagged data is output to wand-style reader.
- Technique can be generalized for many uses  
limited by battery life, mass, and volume.
- For future designs, several thermocouples may be monitored simultaneously (wires must be run to each TC location) with data output from one RFID device.

battery  
inserted  
here



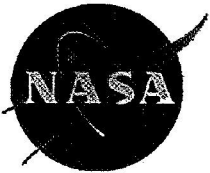
Prototype Active  
SensorTag

Front Surface: transient temperature can exceed 1000°C  
(test in arc jet or use blow torch for demo)



Back Surface: transient temperature below 150°C  
(transient temperature to 340°C may be ok in future versions)





# Components of Active SensorTag

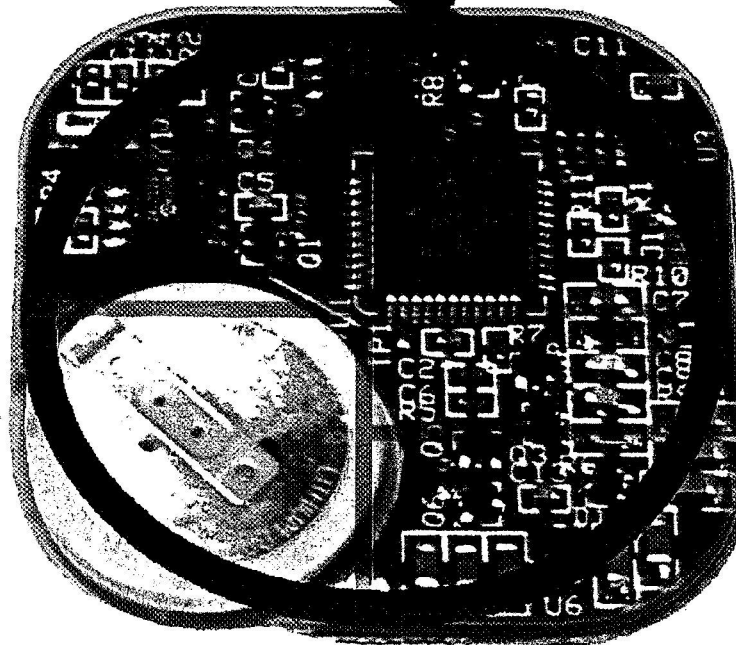


**Thermocouple Probe**

**Real-Time  
Clock**

**Non-Volatile  
Memory**

**Battery**



**Temperature  
Signal Conditioning**

**Micro-Controller**

**RFID Transceiver**

**Power Supply**

**Antenna  
(under-side)**







# Micro Power Cell



## Proposed Power Cell

- uses 1 mg  $^{244}\text{Cm}$
- 0.2 mA, 1 V, 10+ years
- -250 to 600°C
- slab: 40 x 8 x 1 mils
- estimate 80 mCi  
- NRC regulated

## Smaller Power Cell

- need  $\leq 10 \mu\text{Ci}$
- under 25  $\mu\text{A}$



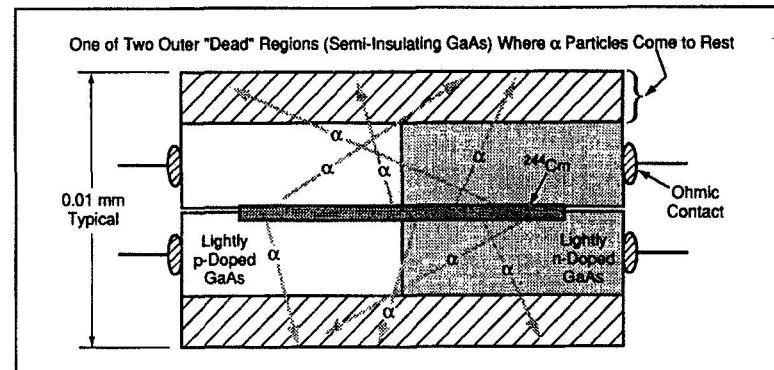
## Generating Electric Power From Alpha-Particle Sources

Long-lived, low-power cells could operate for years at extreme temperatures.

NASA's Jet Propulsion Laboratory, Pasadena, California

Small electric power cells based on the direct conversion of kinetic energy of alpha particles into electricity have been proposed. These cells are expected to function continuously over long times and at temperatures from -250 to 600 °C. They would be made from semiconductors that are stable at high temperatures (most likely GaAs or SiC). The  $\alpha$ -particle sources in these cells will likely be made from curium-244, the radioactivity of which is characterized by a half-life of about 18 years and consists nearly entirely of  $\alpha$  particles. The proposed cells could be useful as power sources for low-power electronic circuits that are required to operate for long times without recharging or external wire power connections, and without relying on sunlight. Potential outer-space and terrestrial applications could include electronic circuits for spacecraft on long interplanetary or deep-space missions, hearing aids, and surgically implanted medical electronic devices.

Earlier attempts at utilizing  $\alpha$  particles to generate electricity have resulted in limited success because of poor planning and lack of proper device designs. Therefore, the planned development of the proposed cells will include studies of factors that affect power-generation efficiency and of the ability of the cells to survive lattice damage induced by impinging  $\alpha$  particles. Computer simulations of the effects of different levels of doping of the semiconductors will be performed in an effort to find



A typical power cell according to the proposal would have this basic configuration. Tentative parameters for a representative cell capable of generating 0.2 mW of power include dimensions of 1 by 0.2 by 0.01 mm, and  $^{244}\text{Cm}$ -source mass of 1 mg.

optimum device designs, and innovative and device engineering is planned to minimize lattice damage from  $\alpha$  particles to maximize device lifetimes and reliabilities.

A basic power cell according to the proposal would include a thin-film  $\alpha$ -particle source sandwiched between two p/n diodes (see figure). One key aspect of design that would clearly distinguish a cell of this type from, say, a photovoltaic cell would be choice of diode dimensions so that  $\alpha$  particles of the given initial kinetic energy ( $\approx 5.9 \text{ MeV}$  for a  $^{244}\text{Cm}$  source) do not stop in the active device volume. The reason for this choice is that  $\alpha$  particles cause severe lattice damage in the vicinities of their stopping locations

because they lose large fractions of their kinetic energy just before stopping.

Therefore, in the proposed design, outer regions of "dead" semiconductor material would be provided and the dimensions of the p, n, and outer regions would be chosen so that the  $\alpha$  particles would come to rest in the outer regions. Although some lattice damage is still expected to occur in the active regions, it has been observed in recent experiments that such damage is continuously annealed during ionization processes in semiconductors.

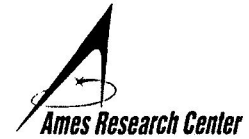
This work was done by Jagdishbhai Patel of Caltech for NASA's Jet Propulsion Laboratory.  
NPO-20654





# Future Work

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- Surface scanner
  - Improve device speed and pattern recognition
  - Make separate step and gap tools
- RFID sensors
  - Mass and volume reduction
  - Use higher frequency components
  - Incorporate error-correcting algorithms
  - Use mass production technology
  - Use MEMS-based sensors and microbatteries
- Improve reader designs for greater read range and faster communication with small devices.
- Prepare for possible flight testing on Shuttle.

